

# ALBEDO AND REFLECTION SPECTRA OF EXTRASOLAR GIANT PLANETS

DAVID SUDARSKY<sup>1</sup>, ADAM BURROWS<sup>1</sup>, & PHILIP PINTO<sup>1</sup>

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## ABSTRACT

We generate theoretical albedo and reflection spectra for a full range of extrasolar giant planet (EGP) models, from Jovian to 51-Pegasi class objects. Our albedo modeling utilizes the latest atomic and molecular cross sections, Mie theory treatment of scattering and absorption by condensates, a variety of particle size distributions, and an extension of the Feautrier technique which allows for a general treatment of the scattering phase function.

We find that due to qualitative similarities in the compositions and spectra of objects within each of five broad effective temperature ranges, it is natural to establish five representative EGP albedo classes. At low effective temperatures ( $T_{\text{eff}} \lesssim 150$  K) is a class of “Jovian” objects (Class I) with tropospheric ammonia clouds. Somewhat warmer Class II, or “water cloud,” EGPs are primarily affected by condensed  $\text{H}_2\text{O}$ . Gaseous methane absorption features are prevalent in both classes. In the absence of non-equilibrium condensates in the upper atmosphere, and with sufficient  $\text{H}_2\text{O}$  condensation, Class II objects are expected to have the highest visible albedos of any class.

When the upper atmosphere of an EGP is too hot for  $\text{H}_2\text{O}$  to condense, radiation generally penetrates more deeply. In these objects, designated Class III or “clear” due to a lack of condensation in the upper atmosphere, absorption lines of the alkali metals, sodium and potassium, lower the albedo significantly throughout the visible. Furthermore, the near-infrared albedo is negligible, primarily due to strong  $\text{CH}_4$  and  $\text{H}_2\text{O}$  molecular absorption, and collision-induced absorption (CIA) by  $\text{H}_2$  molecules. In those EGPs with exceedingly small orbital distance (“roasters”) and  $900 \text{ K} \lesssim T_{\text{eff}} \lesssim 1500 \text{ K}$  (Class IV), a tropospheric silicate layer is expected to exist. In all but the hottest ( $T_{\text{eff}} \gtrsim 1500 \text{ K}$ ) or lowest gravity roasters, the effect of this silicate layer is insignificant due to the very strong absorption by sodium and potassium atoms above the layer. The resonance lines of sodium and potassium are expected to be salient features in the reflection spectra of these EGPs. In the absence of non-equilibrium condensates, we find, in contrast to previous studies, that these Class IV roasters likely have the lowest visible and Bond albedos of any class, rivaling the lowest albedos of our solar system. For the small fraction of roasters with  $T_{\text{eff}} \gtrsim 1500 \text{ K}$  and/or low surface gravity ( $\lesssim 10^3 \text{ cm s}^{-2}$ ; Class V), the silicate layer is located very high in the atmosphere, reflecting much of the incident radiation before it can reach the absorbing alkali metals and molecular species. Hence, the Class V roasters have much higher albedos than those of Class IV.

We derive Bond albedos ( $A_B$ ) and  $T_{\text{eff}}$  estimates for the full set of known EGPs. A broad range in both values is found, with  $T_{\text{eff}}$  ranging from  $\sim 150 \text{ K}$  to nearly  $1600 \text{ K}$ , and  $A_B$  from  $\sim 0.02$  to  $0.8$ .

We find that variations in particle size distributions and condensation fraction can have large quantitative, or even qualitative, effects on albedo spectra. In general, less condensation, larger particle sizes, and wider size distributions result in lower albedos. We explore the effects of non-equilibrium condensed products of photolysis above or within principal cloud decks. As in Jupiter, such species can lower the UV/blue albedo substantially, even if present in relatively small mixing ratios.

*Subject headings:* planetary systems—binaries: general—planets and satellites: general—stars: low-mass, brown dwarfs—radiative transfer—molecular processes—infrared: stars

## 1. INTRODUCTION

Since the discovery of the extrasolar giant planet (EGP), 51 Pegasi b, in 1995 (Mayor & Queloz 1995), an explosion of similar discoveries has followed. To date, there are  $\sim 30$  known planets orbiting nearby stars, which have collectively initiated the new field of extrasolar giant planet research.

While to date most detections have been via Doppler spectroscopy, other promising methods, both ground-based and space-based, are in development. These include (but are not limited to) astrometric techniques (Horner et al. 1998), nulling interferometry (Hinz et al. 1998),

coronagraphic imaging (Nakajima 1994), and spectral deconvolution (Charbonneau et al. 1998). Furthermore, planned space instrumentation such as the NGST (Next Generation Space Telescope) and SIM (Space Interferometry Mission) may prove to be useful for the detection and characterization of EGP systems.

With the current push for new instruments and techniques, we expect that some of these new EGPs will soon be directly detected. One group (Cameron et al. 1999) has claimed a detection in reflected light of the “roaster,”  $\tau$  Boo b, while another group (Charbonneau et al. 1999) has not claimed a detection, but has quoted an upper limit to the albedo which is in conflict with Cameron et al. Our

<sup>1</sup>Department of Astronomy and Steward Observatory, The University of Arizona, Tucson, AZ 85721

theoretical models of EGP albedos are motivated by and can help guide attempts to directly detect EGPs in reflection by identifying their characteristic spectral features and by illuminating the systematics.

The theoretical study of EGP albedos and reflection spectra is still largely in its infancy. Marley et al. (1999) have explored a range of stratosphere-free EGP geometric and Bond albedos using temperature-pressure profiles of EGPs in isolation (i.e. no stellar insolation), while Goukenleuque et al. (1999) modeled 51 Peg in radiative equilibrium, and Seager & Sasselov (1998) explored radiative-convective models of EGPs under strong stellar insolation. In the present study, our purpose is to provide a broader set of models than previous work, and to establish a general understanding of the albedo and reflection spectra of EGPs over the full range of effective temperatures ( $T_{\text{eff}}$ ). Rather than attempting to model these spectra in a fully consistent way for the almost endless combinations of EGP masses, ages, orbital distances, elemental abundances, and stellar spectral types, we concentrate on representative composition classes based loosely on  $T_{\text{eff}}$ . The “Jovian” Class I objects ( $T_{\text{eff}} \lesssim 150$  K) are characterized by the presence of ammonia clouds. (Note that the term, “Jovian”, is used here for convenience, not to imply that this entire class of objects will be identical to Jupiter.) In somewhat warmer objects ( $T_{\text{eff}} \sim 250$  K), ammonia is in its gaseous state, but the upper troposphere contains condensed  $\text{H}_2\text{O}$ . These objects are designated Class II, or “water cloud” EGPs. Class III, or “clear” EGPs, are so named because they are too hot ( $T_{\text{eff}} \gtrsim 350$  K) for significant  $\text{H}_2\text{O}$  condensation and so are not expected to contain any principal condensates, though they are not necessarily completely cloud-free. The hotter EGPs ( $900 \text{ K} \lesssim T_{\text{eff}} \lesssim 1500 \text{ K}$ ; Class IV) include those objects with very small orbital distances (“roasters”) or those at large distances which are massive and young enough to have similar effective temperatures. In either case, the troposphere of such an EGP is expected to contain significant abundances of neutral sodium and potassium gases, as well as a silicate cloud layer. The hottest ( $T_{\text{eff}} \gtrsim 1500$ ) and/or least massive ( $g \lesssim 10^3 \text{ cm s}^{-2}$ ) have a silicate layer located so high in the atmosphere that much of the incoming radiation is shielded from alkali metal and molecular absorption.

We use a planar asymmetric Feautrier method in conjunction with temperature-pressure (T-P) profiles, equilibrium gas abundances (assuming Anders & Grevesse (1989) elemental abundances), and simple cloud models to account for condensed species. The T-P profiles of isolated EGPs, as well as profiles which are nearly isothermal in the outer atmosphere, are utilized. This allows us to bracket the effects of various T-P profiles on the resulting EGP albedo spectra. Like Marley et al. (1999), we generate model albedo and reflection spectra and Bond albedos, assuming a variety of central star spectral types. Similarly, Rayleigh scattering, Raman scattering, Mie extinction due to condensates, and molecular absorption by a host of species are treated. In addition to our broader range of compositions and  $T_{\text{eff}}$  than in Marley et al., we treat the important absorption effects of the alkali metals, include a larger number of relevant condensates (including some non-equilibrium products typical of photolysis), and produce a synthetic albedo spectrum of Jupiter which

is in reasonable agreement with Jupiter’s actual albedo spectrum (Karkoschka 1994) from the soft UV to the near infrared.

Doppler spectroscopy favors the detection of massive companions at small orbital distances and indeed EGPs with very small orbital radii have been found.  $\tau$  Boo b (Butler et al. 1997), 51 Peg b (Mayor & Queloz 1995),  $v$  And b (Butler et al. 1997), HD 75289b (Mayor et al. 1999), HD 187123b (Butler et al. 1998), HD 217107b (Fischer et al. 1999), and HD 209458b (Charbonneau et al. 1999) all have orbital distances of less than 0.1 AU and masses (actually  $M_p \sin i$ ) ranging from  $\sim 0.4$  to 3.4 Jupiter masses. Under stellar insolation, the elevated temperatures of EGPs depend mostly on the level of stellar insolation, rather than on their masses and ages, which would largely determine their  $T_{\text{eff}}$  in isolation. Using simple radiative equilibrium arguments ( $T_{\text{eff}} \propto F_{\text{inc}}^{1/4}$ , where  $F_{\text{inc}}$  is the incident stellar flux), most of the EGPs within 0.1 AU are likely to have very high  $T_{\text{eff}}$  ( $\sim 800$  K to over 1600 K).  $T_{\text{eff}}$  is only weakly dependent on the Bond albedo for a large range of low-to-moderate albedos, varying only  $\sim 20\%$  as the Bond albedo varies from 0.01 to 0.6.

At the other end of the scale, several objects with more traditional orbital distances of  $\gtrsim 1$  AU have been discovered. These EGPs include 16 Cyg Bb (Cochran et al. 1997), 47 UMa b (Butler et al. 1996),  $v$  And d (Marcy et al. 1999), Gl 614b (Mayor et al. 1998), HR 5568b, HR 810b, and HD 210277b (Marcy et al. 1998), and have  $M_p \sin i$  ranging from  $\sim 0.75$  to 5  $M_J$ . At these larger orbital distances, EGPs receive much less stellar radiation and, therefore, have a lower  $T_{\text{eff}}$  ( $\lesssim 300$  K). Still, many other EGPs, such as 70 Vir b (Butler & Marcy 1996), Gl 86 Ab (Queloz et al. 1999), and HD 114762b (Latham et al. 1989), have orbital distances between 0.1 and 1 AU and  $M_p \sin i$  between 0.7 and 10  $M_J$ . Over the full set of currently known EGPs, spectral classes of the central stars range from F7V to M4V.

The albedo of an object is simply the fraction of light that the object reflects. However, there are several different types of albedos. The *geometric* albedo refers to the reflectivity of the object at full phase ( $\Phi = 0$ , where  $\Phi$  represents the object’s phase angle) relative to that by a perfect Lambert disk of the same radius under the same incident flux. Since planets are essentially spheres, the factor projecting a unit surface onto a disk orthogonal to the line of sight is given by  $\cos \phi \sin \theta$ , where  $\phi$  is the object’s longitude (defined to be in the observer-planet-star plane) and  $\theta$  is its polar angle ( $\frac{\pi}{2}$  - latitude). The geometric albedo is given by integrating over the illuminated hemisphere:

$$A_g = \frac{1}{\pi I_{\text{inc}}} \int_{\phi=-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{\theta=0}^{\pi} I(\phi, \theta, \Phi = 0) \cos \phi \sin \theta d\Omega, \quad (1)$$

where  $I_{\text{inc}}$  is the incident specific intensity,  $\pi I_{\text{inc}}$  is the incident flux, and  $I(\phi, \theta, \Phi = 0)$  is the emergent intensity. More generally,  $I = I(\phi, \theta, \Phi; \phi_0, \theta_0)$ , but at full phase all incident angles ( $\phi_0, \theta_0$ ) are equal to the emergent ones. The geometric albedo is usually given as a function of wavelength, although it is sometimes averaged over a wavelength interval and stated as a single number.

The *spherical* albedo,  $A_s$ , refers to the fraction of incident light reflected by a sphere at all angles. Usually stated

as a function of wavelength, it is obtained by integrating the reflected flux over all phase angles. The flux ( $F(\Phi)$ ) as a function of phase angle ( $\Phi$ ) is given by the more general form of eq. (1). Assuming unit radius (Chamberlain & Hunten 1987),

$$F(\Phi) = \int_{\phi=\Phi-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{\theta=0}^{\pi} I(\phi, \theta, \Phi; \phi_0, \theta_0) \cos \phi \sin \theta d\Omega. \quad (2)$$

The spherical albedo is obtained by integrating  $F(\Phi)$  over all solid angles:

$$A_s = \frac{1}{\pi I_{inc}} \int_{4\pi} F(\Phi) d\Omega = \frac{2}{I_{inc}} \int_0^\pi F(\Phi) \sin \Phi d\Phi. \quad (3)$$

Note that the spherical and geometric albedos are related by  $A_s = A_g q$ , where

$$q = \frac{2}{F(\Phi=0)} \int_0^\pi F(\Phi) \sin \Phi d\Phi \quad (4)$$

is known as the phase integral.

The *Bond* albedo,  $A_B$ , is the ratio of the total reflected and total incident powers. It is obtained by weighting the spherical albedo by the spectrum of the illuminating source and integrating over all wavelengths:

$$A_B = \frac{\int_0^\infty A_{s,\lambda} I_{inc,\lambda} d\lambda}{\int_0^\infty I_{inc,\lambda} d\lambda}, \quad (5)$$

where the  $\lambda$  subscript signifies that the incident intensity varies with wavelength.

Spherical, geometric, and Bond albedos of objects are strong functions of their compositions. Within the solar system, they vary substantially with wavelength, and from object to object. At short wavelengths, gaseous atmospheres can have high albedos due to Rayleigh scattering, and low albedos at longer wavelengths due to molecular ro-vibrational absorption. Icy condensates, whether they reside on a surface or are present in an upper atmosphere, are highly reflective and increase the albedo. Other condensates, such as silicates or non-equilibrium products of photolysis, can lower the albedo substantially over a broad wavelength region.

Some of the lowest albedos seen in the Solar System are those of asteroids containing large amounts of carbonaceous material. Many have Bond albedos of less than 0.03 (Lebofsky et al 1989). The Bond albedo of the Earth is 0.30 (Stephens et al. 1981) and that of the Moon is 0.11 (Buratti 1996). Jupiter and Saturn have somewhat higher Bond albedos, both near 0.35 (Conrath et al. 1989).

In §??, we describe our approach to modeling EGPs. Section ?? describes our radiative transfer method, §?? contains a discussion of molecular absorption and scattering, and §?? describes the properties of and our treatment of the relevant condensates in EGP atmospheres. In §??, we discuss the application of our methods to Jupiter, §?? contains our EGP model albedo and reflection spectra results, as well as  $T_{\text{eff}}$  and Bond albedo estimates for currently known EGPs, and §?? describes the effects of varying key parameters of the models. We summarize our results in §??.

## 2. EXTRASOLAR GIANT PLANET MODELS

Depending upon their proximity to their central stars as well as their masses and ages, EGP effective temperatures likely span a large range, from below 100 K to well over 1600 K, with highly varying temperature-pressure-composition profiles. However, an EGP's outer atmospheric composition, rather than its specific temperature-pressure profile, is of primary importance in modeling albedos and reflection spectra. With our composition classes, we encompass the range of behaviors of EGP albedos and reflection spectra. We do not model emission spectra, nor do our models account for object-specific details, such as elemental abundance differences or cloud patchiness. EGPs are surely at least as rich and varied as the planets of our solar system, but simple modeling reveals many interesting systematics.

### 2.1. Temperature-Pressure Profiles

Ideally, temperature (T)-pressure (P) profiles are computed directly via radiative equilibrium models of EGPs under stellar insolation. A move toward such models for very strong stellar insolation has been made by Seager & Sasselov (1998) and Goukenleuque et al. (1999), while for lower temperature objects, Marley et al. (1999) utilize T-P profiles of isolated EGPs. The main effect of stellar insolation on the T-P profile of an EGP is to make the outer atmosphere more nearly isothermal. Studies of strong stellar insolation conclude that a stratosphere does not exist in the high-temperature roasters (Seager & Sasselov 1998; Goukenleuque et al. 1999). However, it is not completely clear what might occur in the upper atmosphere if ultraviolet photochemical processes are fully modeled. Under solar insolation, Jupiter and Saturn do exhibit stratospheres, and we suspect that the Class I EGPs are likely to have stratospheres as well. In an albedo spectrum, the existence of a stratosphere is made manifest mainly by the scattering and absorption effects of non-equilibrium aerosols which reside there. Additionally, photochemical processes in the stratosphere may be the origin of “chromophores,” non-equilibrium solids which settle near or in the upper cloud layers and are largely responsible for the coloration of Jupiter.

To bracket the range of albedos under stellar insolation, we use two sets of pressure-temperature profiles. The first is a subset of profiles for theoretical isolated objects (Marley et al. 1999; Marley 1998; Burrows et al. 1997) with  $T_{\text{eff}} \approx 130$  K (representing an isolated Class I EGP), 250 K (Class II), 600 K (Class III), and 1200 K (Class IV). We estimate that these representative isolated T-P profiles are valid for surface gravities between  $\sim 3 \times 10^3$  to  $3 \times 10^4$  cm s<sup>-2</sup>. A set of modified profiles is obtained by altering these isolated profiles to simulate a stellar insolated T-P profile by using the model results of Seager & Sasselov (1998) as a guide. To approximate the T-P profiles of the very hottest close-in objects (Class V), we scale the 1200 K profile up to 1700 K. We stress that these modified profiles are very approximate, but along with the isolated T-P profiles, they bracket a broad range of possible EGP T-P profiles.

Figure 1 shows both the isolated and modified T-P profiles for Classes I through IV, as well as our modified Class V profile. Also shown are condensation curves, which indicate the highest temperatures and pressures at which

species can condense. Cloud bases are located approximately where the profiles intersect the condensation curves (dotted curves). Class I (“Jovian”) objects contain both ammonia and deeper water cloud layers, while water is likely the only principal condensate present in the tropospheres of Class II objects. (As shown in Figure 1, a thin ammonia haze layer might appear very high in the atmosphere for an isolated Class II T-P profile.) The Class III T-P profile doesn’t cross any principal condensation curves in the upper atmosphere, regardless of the level of stellar insolation. Finally, the Class IV and V roasters contain a silicate cloud deck and a deeper iron cloud deck throughout the full range of possible T-P profiles, though their cloud depths differ considerably.

## 2.2. Determination of Gaseous Abundances

Using the analytic formulae in Burrows & Sharp (1999), we calculate gaseous mixing ratios of the main compounds of carbon, oxygen, and nitrogen ( $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ ,  $\text{NH}_3$ ,  $\text{N}_2$ ) over the full range of temperatures and pressures in the model EGP atmospheres.  $\text{H}_2$  and He mixing ratios are set according to Anders & Grevesse (1989) solar abundances, and the  $\text{H}_2\text{S}$  mixing ratio is set in accordance with the Anders & Grevesse abundance of sulfur ( $\sim 3 \times 10^{-5}$ ). The abundances of the alkali metals (Na, K, Rb, Cs), important in the Class III through Class V EGPs, are calculated numerically using the formalism of Burrows & Sharp (1999).

Overall, the effect of differences in the T-P profile on gaseous mixing ratios tends to be greatest for the Class IV objects due to the temperature and pressure dependences of neutral alkali metal mixing ratios and the fact that the T-P profiles are in the vicinity of the  $\text{CH}_4/\text{CO}$  and  $\text{NH}_3/\text{N}_2$  equilibrium curves. From the standpoint of gaseous abundances, the T-P profiles have little effect on the albedos of cooler EGPs.

## 2.3. Cloud Modeling

Our treatment of clouds in our fiducial EGP models assumes that the gaseous form of a condensable species is completely depleted above the cloud deck and that the species settles within the cloud layer in its condensed form. The base of the cloud resides where the T-P profile of the EGP meets the condensation curve of the given species, and the cloud top is simply set at one pressure scale height above the base. Not all of the given condensable within the cloud is in condensed form. Rather, at the base of the cloud, the gaseous form is assumed to be at the saturation vapor pressure. For a given abundance of a condensable, if we assume that the portion of the condensable which exceeds the saturation vapor pressure is entirely in condensed form, we will refer to this as “full condensation.” However, as in Jupiter’s outer atmosphere (see §??), it is possible that the condensation fraction will be smaller. Hence, we retain the condensation fraction as a parameter. Furthermore, the particle size distributions in EGP atmospheres are impossible to ascertain at this point, so particle size remains a free parameter as well.

The standard model for Jupiter lends some support to our prescription for clouds. The base of Jupiter’s ammonia cloud deck resides approximately where its T-P profile meets the  $\text{NH}_3$  condensation curve ( $\sim 0.7$  bar) and the cloud tops extend roughly one pressure scale height, to  $\sim$

0.3 bar (West et al. 1986; Griffith et al. 1992). Although present,  $\text{NH}_3$  gas is largely depleted above the cloud layer.

In the case of silicate condensation, where the condensate and gas molecules are not identical (unlike  $\text{NH}_3$  and  $\text{H}_2\text{O}$ ), the condensate abundance is estimated by the Anders & Grevesse abundance of the limiting species. We use enstatite ( $\text{MgSiO}_3$ ; though a number of other silicates with differing optical properties are certainly present), for which the limiting element is silicon. For the full condensation limit, it is assumed that the entire mass of silicon above the pressure of the cloud base settles into  $\text{MgSiO}_3$  within the cloud.

## 3. RADIATIVE TRANSFER METHOD

Due to the forward scattering from condensates in EGP atmospheres, an appropriate radiative transfer method must allow for a forward-backward asymmetric scattering phase function. Although the conventional Feautrier method (e.g. Mihalas 1978) does not allow for such an asymmetry, a straightforward extension of this technique can be derived by separating the source function into upward- and downward-propagating rays (Mihalas 1980; Milkey et al. 1975).

At first thought, it may seem inappropriate to use a planar transfer code in the modeling of albedos and reflection spectra from spherical objects. However, it is fairly straightforward to derive the equivalence between uniform radiation from one direction onto a unit sphere and uniform radiation from  $2\pi$  steradians onto a plane with unit area. Hence, provided that we set the incident intensity to be uniform in angle, the spherical albedo is the ratio of the outward and incident fluxes.

The fundamental transfer equation is

$$\mu \frac{\partial I(\mu)}{\partial \tau} = I(\mu) - S(\mu), \quad (6)$$

where the source function is given by

$$S(\mu) = \frac{1}{2} \sigma \int_{-1}^1 R(\mu, \mu') I(\mu') d\mu' \quad (7)$$

and the thermal term is neglected in this albedo study.  $R(\mu, \mu')$  is the azimuth-independent angular redistribution function (azimuthal symmetry is assumed) and  $\sigma$  is the single-scattering albedo,  $\sigma = \sigma_{\text{scat}}/\sigma_{\text{ext}}$ , where  $\sigma_{\text{scat}}$  is the scattering cross section and  $\sigma_{\text{ext}}$  is the extinction cross section. Separated into upward ( $I^+$ ) and downward ( $I^-$ ) components, the transfer equation becomes

$$\mu \frac{\partial I^+(\mu)}{\partial \tau} = I^+(\mu) - S^+(\mu) \quad (8)$$

and

$$-\mu \frac{\partial I^-(\mu)}{\partial \tau} = I^-(\mu) - S^-(\mu), \quad (9)$$

where the source functions are given by

$$S^+(\mu) = \frac{1}{2} \sigma \int_0^1 [R(\mu, \mu') I^+(\mu') + R(\mu, -\mu') I^-(\mu')] d\mu' \quad (10)$$

and

$$S^-(\mu) = \frac{1}{2}\sigma \int_0^1 [R(-\mu, \mu')I^+(\mu') + R(-\mu, -\mu')I^-(\mu')] d\mu' \quad (11)$$

for the  $I^+$  and  $I^-$  equations, respectively.

Forming symmetric and antisymmetric averages, and using the Feautrier variables,  $u = \frac{1}{2}(I^+ + I^-)$  and  $v = \frac{1}{2}(I^+ - I^-)$ , eqs. (8) and (9) are rewritten as

$$\mu \frac{\partial v(\mu)}{\partial \tau} = u(\mu) - \frac{1}{2} [S^+(\mu) + S^-(\mu)] \quad (12)$$

and

$$\mu \frac{\partial u(\mu)}{\partial \tau} = v(\mu) - \frac{1}{2} [S^+(\mu) - S^-(\mu)]. \quad (13)$$

Since  $R(\mu, \mu')$  depends only upon the angle between  $\mu$  and  $\mu'$ , the following symmetries exist:

$$R(\mu, \mu') = R(-\mu, -\mu') \quad (14)$$

$$R(-\mu, \mu') = R(\mu, -\mu'). \quad (15)$$

With the definitions,  $R^+(\mu, \mu') = R(\mu, \mu') + R(-\mu, \mu')$  and  $R^-(\mu, \mu') = R(\mu, \mu') - R(-\mu, \mu')$ , eqs. (12) and (13) become

$$\mu \frac{\partial v}{\partial \tau} = u - \frac{1}{2}\sigma \int_0^1 R^+(\mu, \mu')u(\mu')d\mu' \quad (16)$$

and

$$\mu \frac{\partial u}{\partial \tau} = v - \frac{1}{2}\sigma \int_0^1 R^-(\mu, \mu')v(\mu')d\mu'. \quad (17)$$

This system of first-order equations is discretized for numerical computation by replacing the derivatives with difference quotients, and by substituting Gaussian quadrature sums for the integrals. The principal equations then become

$$\mu_i \frac{v_{d,i} - v_{d-1,i}}{\Delta\tau_d} = u_{d,i} - \frac{1}{2}\sigma \sum_j \omega_j R^+(\mu_i, \mu_j)u_{d,j} \quad (18)$$

and

$$\mu_i \frac{u_{d+1,i} - u_{d,i}}{\Delta\tau_{d+\frac{1}{2}}} = v_{d,i} - \frac{1}{2}\sigma \sum_j \omega_j R^-(\mu_i, \mu_j)v_{d,j}, \quad (19)$$

where  $d$  signifies a given depth zone ( $d = 1, \dots, D$ ), and  $i$  and  $j$  signify angular bins ( $i, j = 1, \dots, N$ ).  $\Delta\tau_{d+\frac{1}{2}}$  equals  $\tau_{d+1} - \tau_d$  and  $\Delta\tau_d$  equals  $\frac{1}{2}(\Delta\tau_{d+\frac{1}{2}} + \Delta\tau_{d-\frac{1}{2}})$ . To achieve numerical stability,  $\Delta\tau$  is staggered by half a zone in eq. (19) relative to eq. (18). The  $\omega_j$  are the Gaussian weights.

The upper boundary conditions are given by the relations,  $u_{1,i} - v_{1,i} = I_i^-$  and

$$\mu_i \frac{u_{2,i} - u_{1,i}}{\Delta\tau_{\frac{1}{2}}} = u_{1,i} - I_i^- - \frac{1}{2}\sigma \sum_j \omega_j [u_{1,j} - I_j^-] R^-(\mu_i, \mu_j), \quad (20)$$

where  $I_i^-$  and  $I_j^-$  signify the incident intensity as a function of angle at the surface. We set  $I^-$  to unity at all angles since only the *ratio* of the outward and inward fluxes

determines the spherical albedo. The lower boundary conditions are given by  $u_{D,i} + v_{D,i} = I_i^+$  and

$$\mu_i \frac{u_{D,i} - u_{D-1,i}}{\Delta\tau_{D-\frac{1}{2}}} = I_i^+ - u_{D,i} - \frac{1}{2}\sigma \sum_j \omega_j [I_j^+ - u_{D,j}] R^-(\mu_i, \mu_j), \quad (21)$$

where  $I_i^+$  and  $I_j^+$  signify the outward-traveling intensity at the base of the atmosphere (set to zero in this study).

The system of equations can be represented by angle matrices ( $\mathbf{A}_d, \mathbf{B}_d, \mathbf{C}_d, \dots$ ) and column vectors ( $\mathbf{u}_d$  and  $\mathbf{v}_d$ ) such that equations (18) and (19) can be written as

$$\mathbf{A}_d \mathbf{v}_{d-1} + \mathbf{B}_d \mathbf{u}_d + \mathbf{C}_d \mathbf{v}_d = 0 \quad (22)$$

and

$$\mathbf{D}_d \mathbf{u}_d + \mathbf{E}_d \mathbf{v}_d + \mathbf{F}_d \mathbf{v}_{d+1} = 0. \quad (23)$$

Given  $D$  depth zones and  $N$  angles, the system results in a block matrix containing  $[2 \times D]^2$  submatrices, each of order  $N$ . Implementing the boundary conditions described above, this system is solved directly via LU decomposition and substitution.

Our atmosphere models utilize 100 optical depth zones with logarithmic sizing near the surface, where higher resolution is essential, and a continuous transition to linear zoning at depth. Sixteen polar angular bins per hemisphere are used.

### 3.1. Quantitative Comparison for Uniform Atmospheres

In order to test our asymmetric Feautrier code, we compare our resulting spherical albedos for uniform atmosphere models with those derived employing both Monte Carlo and analytic techniques. Van de Hulst (1974) derived a solution for the spherical albedo of a planet covered with a semi-infinite homogeneous cloud layer. Given a single-scattering albedo of  $\sigma (= \sigma_{\text{scat}}/\sigma_{\text{ext}})$  and a scattering asymmetry factor of  $g = \langle \cos \theta \rangle$  (the average cosine of the scattering angle), van de Hulst's expression for the spherical albedo is

$$A_s \approx \frac{(1 - 0.139s)(1 - s)}{1 + 1.170s}, \quad (24)$$

where

$$s = \left[ \frac{1 - \sigma}{1 - \sigma g} \right]^{1/2}. \quad (25)$$

Figure 2 shows the spherical albedo of a homogeneous, semi-infinite atmosphere as a function of scattering asymmetry factor and single scattering albedo. Along with van de Hulst's semi-analytic curves are our asymmetric Feautrier and Monte Carlo model results using a Henyey-Greenstein scattering phase function,

$$p(\theta) = \frac{1 - g^2}{(1 + g^2 - 2g \cos \theta)^{3/2}}. \quad (26)$$

For nearly all values of  $g$  and  $\sigma$ , the agreement is very good, differing by under 1%. There are slightly larger variations when both  $g$  and  $\sigma$  approach unity due to the finite number of angles and depth zones used in our numerical models, but in actual planetary or EGP atmospheres, this corner of parameter space is rarely realized.

Real planetary atmospheres are usually highly stratified and the optical depth is a strong function of wavelength.

Given the atmospheric temperature-pressure-composition profile, an appropriate conversion to optical depth is required. Assuming hydrostatic equilibrium and using an ideal gas equation of state, this conversion is

$$d\tau = \frac{\sigma_{ext}(P)}{g\mu(P)}dP, \quad (27)$$

where  $\sigma_{ext}$  is the effective extinction cross section per particle at depth  $P$ ,  $\mu$  is the mean molecular weight, and  $g$  is the surface gravity (assumed constant because the depth of the effective atmosphere is a very small fraction of the planet's radius).

#### 4. ATOMIC AND MOLECULAR SCATTERING AND ABSORPTION

The gases present in EGP atmospheres are many (Burrows and Sharp 1999). However, only some of them have the requisite abundances and cross sections at the temperatures and pressures of upper EGP atmospheres to have significant spectral effects in the visible and near-infrared. These species include  $H_2$ ,  $CH_4$ ,  $H_2O$ ,  $NH_3$ ,  $CO$ , and  $H_2S$ . Additionally,  $Na$  and  $K$  are important absorbers in Class III, IV, and V EGPs.

Of course,  $H_2$  is the most abundant species, followed by helium. The dominant carbon-bearing molecule is a function of both temperature and pressure. Chemical equilibrium modeling (Burrows and Sharp 1999; Fegley & Lodders 1996) shows that, at solar metallicity,  $CH_4$  will dominate over  $CO$  in most EGP atmospheres. At high temperatures, the  $CO$  abundance overtakes that of  $CH_4$  ( $\sim 1100$  K at 1 bar;  $\sim 1400$  K at 10 bars). There is a similar transition for the nitrogen-bearing molecules:  $NH_3$  dominates at low temperatures, but it is overtaken by  $N_2$  at higher temperatures ( $\sim 700$  K at 1 bar;  $\sim 900$  K at 10 bars). Some species condense into solids at low temperatures, thereby depleting the gaseous phase. In particular,  $NH_3$  condenses below 150–200 K (depending upon pressure), as does  $H_2O$  below 250–300 K.

At visible and near-infrared wavelengths, molecular absorption is due to ro-vibrational transitions, so molecular opacity is a very strong function of wavelength. Even when no permanent dipole moment exists, such as with the  $H_2$  molecule, the high gas pressures in EGP atmospheres can induce temporary dipole moments via collisions. This Collision Induced Absorption (CIA) is responsible for broad  $H_2$ - $H_2$  (and  $H_2$ -He) absorption bands in Jupiter and Saturn (Zheng & Borysow 1995; Trafton 1967).

The temperature- and pressure-dependent gaseous opacities are obtained from a variety of sources—a combination of theoretical and experimental data as referenced in Burrows et al. (1997). Additionally, for this study the  $CH_4$  opacity was extended continuously into the visible wavelength region using the data of Strong et al. (1993) and a methane absorption spectrum from Karkoschka (1994). These two data sets were then extrapolated in temperature and pressure by scaling with existing temperature and pressure-dependent near-infrared  $CH_4$  data (Burrows et al. 1997 and references therein).

Many prominent molecular absorption features may be seen in EGP albedo and reflection spectra. At relatively low temperatures, broad  $H_2$ - $H_2$  and  $H_2$ -He CIA bands peak at  $\sim 0.8 \mu m$ ,  $1.2 \mu m$ , and  $2.4 \mu m$ . At higher temperatures and pressures, the CIA cross sections become

larger at all wavelengths. CIA is especially important in cloud-free gaseous objects, where incident radiation is absorbed deeper in the atmosphere.  $NH_3$  absorption bands shortward of  $2.5 \mu m$  occur at  $\sim 1.5 \mu m$ ,  $2.0 \mu m$ , and  $2.3 \mu m$ . (Note that our database does not contain the visible bands of ammonia.)  $H_2O$  absorption occurs at  $\sim 0.6 \mu m$ ,  $0.65 \mu m$ ,  $0.7 \mu m$ ,  $0.73 \mu m$ ,  $0.82 \mu m$ ,  $0.91 \mu m$ ,  $0.94 \mu m$ ,  $1.13 \mu m$ ,  $1.4 \mu m$ ,  $1.86 \mu m$ , and  $2.6 \mu m$ . A large number of  $CH_4$  features appear in the visible and near-infrared. Some of the more prominent ones occur at  $\sim 0.54 \mu m$ ,  $0.62 \mu m$ ,  $0.67 \mu m$ ,  $0.7 \mu m$ ,  $0.73 \mu m$ ,  $0.79 \mu m$ ,  $0.84 \mu m$ ,  $0.86 \mu m$ ,  $0.89 \mu m$ ,  $0.99 \mu m$ ,  $1.15 \mu m$ ,  $1.4 \mu m$ ,  $1.7 \mu m$ , and  $2.3 \mu m$ .  $CO$  absorption bands occur at  $\sim 1.2 \mu m$ ,  $1.6 \mu m$ , and  $2.3 \mu m$  and  $H_2S$  features may be found at  $\sim 0.55 \mu m$ ,  $0.58 \mu m$ ,  $0.63 \mu m$ ,  $0.67 \mu m$ ,  $0.73 \mu m$ ,  $0.88 \mu m$ ,  $1.12 \mu m$ ,  $1.6 \mu m$ , and  $1.95 \mu m$ . Of course, depending upon mixing ratios and cross sections, only some of these features will appear in a given EGP albedo spectrum.

Strong pressure-broadened lines of neutral sodium and potassium are expected to dominate the visible albedos of Class III and Class IV EGPs. The most prominent absorption lines of sodium occur at 3303 Å, 5890 Å, and 5896 Å, while those of potassium occur at 4044 Å, 7665 Å, and 7699 Å.

Atomic and molecular scattering includes conservative Rayleigh scattering as well as non-conservative Raman scattering. In the case of Rayleigh scattering, cross sections are derived from polarizabilities, which are in turn derived from refractive indices. Since the refractive indices are readily available at 5893 Å (Weast 1983), the Rayleigh cross sections are derived at this wavelength via,

$$\sigma_{Ray} = \frac{8}{3}\pi k^4 \left( \frac{n-1}{2\pi L_0} \right)^2, \quad (28)$$

where  $k$  is the wavenumber at this wavelength ( $2\pi/\lambda \simeq 106621 \text{ cm}^{-1}$ ) and  $L_0$  is Loschmidt's number. Assuming that the refractive indices are not strong functions of wavelength, we simply extrapolate these cross sections as  $\lambda^{-4}$ .

Raman scattering by  $H_2$  involves the shift of continuum photons to longer or shorter wavelengths as they scatter off  $H_2$ , exciting or de-exciting rotational and vibrational transitions. Raman scattering is not coherent in frequency, so a rigorous treatment is not possible with our transfer code. Instead, we adopt the approximate method introduced by Pollack et al. (1986) and used by Marley et al. (1999) in their albedo study. At a given wavelength, the single scattering albedo within a particular depth zone is approximated by

$$\sigma = \frac{\sigma_{Ray} + \sigma'_{scat} + (f_{\lambda^*}/f_{\lambda})\sigma_{Ram}}{\sigma_{Ray} + \sigma'_{ext} + \sigma_{Ram}}, \quad (29)$$

where  $f_{\lambda}$  denotes the spectrum of incident radiation (the spectrum of an EGP's central star),  $\lambda^{*-1} = \lambda^{-1} + \Delta\lambda^{-1}$ , where  $\Delta\lambda$  is the wavelength of the  $H_2$  vibrational fundamental ( $\Delta\lambda^{-1} = 4161 \text{ cm}^{-1}$ ),  $\sigma_{Ram}$  is the Raman cross section, and  $\sigma'_{scat}$  and  $\sigma'_{ext}$  are the effective condensate scattering and extinction cross sections, respectively. Raman scattering may be significant in deep gaseous planetary atmospheres, where it can lower the UV/blue albedo by up to  $\sim 15\%$  (Cochran & Trafton 1978). However,

our models show that in higher temperature EGP atmospheres, alkali metal absorption can dominate over this wavelength region, while in cooler EGP atmospheres, condensates largely dominate. Over our full set of EGP models, we find that Raman scattering is relatively insignificant.

## 5. MIE THEORY AND OPTICAL PROPERTIES OF CONDENSATES

Condensed species in EGP atmospheres range from ammonia ice in low temperature objects to silicate grains at high temperatures. Some of the condensates relevant to EGP atmospheres include  $\text{NH}_3$  ( $\lesssim 150\text{--}200\text{K}$ ),  $\text{NH}_4\text{SH}$  ( $\lesssim 200\text{K}$ ),  $\text{H}_2\text{O}$  ( $\lesssim 250\text{--}300\text{K}$ ), low-abundance sulfides and chlorides ( $\lesssim 700\text{--}1100\text{K}$ ), silicates such as  $\text{MgSiO}_3$  ( $\lesssim 1600\text{--}1800\text{K}$ ), and iron or iron-rich compounds ( $\lesssim 1900\text{--}2300\text{K}$ ). Additionally, photochemical processes in the upper atmosphere can produce non-equilibrium condensates. Stratospheric hazes may be composed of polyacetylene (Bar-Nun et al. 1988) and other aerosols. Chromophores, those non-equilibrium species which cause the coloration of Jupiter and Saturn, might include  $\text{P}_4$  (Noy et al. 1981) or organic species similar to Titan tholin (Khare & Sagan 1984).

Condensates can have drastic effects on EGP reflection spectra, increasing the albedo at most wavelengths, but sometimes depressing the albedo in the UV/blue. Of course, those condensates which are higher in the atmosphere will generally have a greater effect than those which reside more deeply. The presence and location of a particular condensed species is determined largely by an object's T-P profile, and by the tendency of the condensate to settle (due to rain) at a depth in the atmosphere near the region where the T-P profile crosses the condensation curve. Hence, a given low-temperature ( $T_{\text{eff}} \lesssim 150\text{K}$ ) atmosphere might consist of an ammonia cloud deck high in the troposphere and a water cloud deck somewhat deeper, with purely gaseous regions above, beneath, and between the clouds. Similarly, a high-temperature ( $T_{\text{eff}} \sim 1200\text{K}$ ) atmosphere might consist of a tropospheric silicate cloud deck above a deeper iron cloud deck. Depending upon the amount of condensate in the upper cloud and the wavelength region, the presence of deeper clouds may or may not have any effect on the albedo and reflection spectrum.

The scattering and absorption of electromagnetic radiation by condensed species in planetary atmospheres is a very complex problem. The extinction properties of ices, grains, and droplets of various sizes, shapes, and compositions cannot be described accurately by simple means. Most often, these properties are approximated by Mie Theory, which describes the solution of Maxwell's equations inside and outside a homogeneous sphere with a given complex refractive index.

We use a full Mie Theory approach which utilizes the formalism of van de Hulst (1957) and Deirmendjian (1969), and results in scattering and extinction cross sections as well as a scattering asymmetry factor,  $g = \langle \cos \theta \rangle$ , given the complex index of refraction and particle radius ( $a$ ). Larger particles require an increasing number of terms in an infinite series to describe these parameters accurately, and so they require more computing time. But while the cross sections and scattering asymmetry factors of small-

to moderately-sized particles ( $2\pi a/\lambda \lesssim 75$ ) vary substantially with wavelength, these variations are greatly reduced for larger spheres. For these larger particles, we use an asymptotic form of the Mie equations outlined fully by Irvine (1965). Interpolation between the full Mie theory results and these asymptotic limits yields the parameters for large particles. However, inherent assumptions in the asymptotic form of the Mie equations render them inadequate for the computation of the scattering cross sections in the weak-absorption limit ( $n_{\text{imag}} \lesssim 10^{-3}$ ), in which case we use the geometric optics approximation (Bohren & Huffman 1983),

$$Q_{\text{sca}} = 2 - \frac{8}{3} \frac{n_{\text{imag}}}{n_{\text{real}}} \left[ n_{\text{real}}^3 - (n_{\text{real}}^2 - 1)^{3/2} \right] x, \quad (30)$$

where  $Q_{\text{sca}}$  is the usual scattering coefficient (the ratio of the scattering cross section to the geometric cross section),  $x$  is the size parameter ( $= 2\pi a/\lambda$ ),  $n_{\text{real}}$  is the real index of refraction, and  $n_{\text{imag}}$  is the imaginary component of the refractive index.

The principal condensates to which we have applied Mie theory include  $\text{NH}_3$  ice,  $\text{H}_2\text{O}$  ice, and  $\text{MgSiO}_3$  (enstatite), where the optical properties, namely the complex indices of refraction, were obtained from Martonchik et al. (1984), Warren (1984), and Dorschner et al. (1995), respectively. The complex refractive indices of  $\text{NH}_3$  were interpolated in the  $0.7$  to  $1.4 \mu\text{m}$  wavelength region, due to the lack of data there.

Each of these condensates has absorption features, as is made evident by the behavior of the imaginary index of refraction (Figure 3). Shortward of  $2.5 \mu\text{m}$ ,  $\text{NH}_3$  ice absorption occurs at  $\sim 1.55 \mu\text{m}$ ,  $1.65 \mu\text{m}$ ,  $2.0 \mu\text{m}$ , and  $2.25 \mu\text{m}$ .  $\text{H}_2\text{O}$  ice produces broader features at  $\sim 1.5 \mu\text{m}$  and  $2.0 \mu\text{m}$ . Enstatite is mostly featureless below  $2.5 \mu\text{m}$ , except shortward of  $\sim 0.35 \mu\text{m}$ .

The non-equilibrium condensates to which we have applied Mie theory include phosphorus (Noy et al. 1981), tholin (Khare & Sagan 1984), and polyacetylene (Bar-Nun et al. 1988).  $\text{P}_4$  and tholin are chromophore candidates, particularly for the coloration of Jupiter and Saturn, due to their large imaginary indices of refraction in the UV/blue (Figure 4) and plausibility of production. A somewhat yellowish allotrope of phosphorus,  $\text{P}_4$  was produced in the laboratory by Noy et al. (1981) by UV irradiation of an  $\text{H}_2/\text{PH}_3$  gaseous mixture. It is believed that this same process may be responsible for its production in Jupiter. Tholin is a dark-reddish organic solid (composed of over 75 compounds) synthesized by Khare and Sagan (1984) by irradiation of gases in a simulated Titan atmosphere. It is believed that a tholin-like solid may be produced similarly in giant planet atmospheres. Polyacetylenes, polymers of  $\text{C}_2\text{H}_2$ , were investigated by Bar-Nun et al. (1988) and likely are an optically dominant species in the photochemical stratospheric hazes of giant planets, where hydrocarbons are abundant (Edgington et al. 1996; Noll et al. 1986).

Cloud particle sizes are not easily modeled and are a strong function of the unknown meteorology in EGP atmospheres. Inferred particle sizes in solar system giant planet atmospheres can guide EGP models, though they range widely from fractions of a micron to tens of microns.

We have investigated various particle size distributions. A commonly used distribution, and the one that we use in

our fiducial models, is

$$n(a) \propto \left(\frac{a}{a_0}\right)^6 \exp\left[-6\left(\frac{a}{a_0}\right)\right], \quad (31)$$

which reproduces the distributions in cumulus water clouds in Earth’s atmosphere fairly well if the peak of the distribution is  $a_0 \sim 4\mu\text{m}$  (Deirmendjian 1964). Stratospheric aerosols—at least those in Earth’s stratosphere—can be represented by the “haze” distribution (Deirmendjian 1964),

$$n(a) \propto \frac{a}{a_0} \exp\left[-2\left(\frac{a}{a_0}\right)^{1/2}\right]. \quad (32)$$

## 6. THE ALBEDO OF JUPITER

Jupiter is an important testbed for the theory of albedos, since full-disk geometric albedo spectra have been obtained (Karkoschka 1994, 1998), and because space-based and ground-based studies have provided a fair amount of information concerning Jupiter’s atmosphere. At visible and near-infrared wavelengths, Jupiter’s upper troposphere and stratosphere shape its albedo spectrum. According to the standard model, a somewhat heterogeneous cloud deck extends from  $\sim 0.3$  to  $0.7$  bars in the troposphere (West et al. 1986; Griffith et al. 1992). Although the bulk of the cloud deck consists primarily of particles at least  $10\mu\text{m}$  in size, a layer of smaller particles ( $\sim 0.5$ – $1.0\mu\text{m}$ ) resides near the cloud tops (West et al. 1986; Pope et al. 1992). Beneath this upper cloud deck is a  $\text{NH}_4\text{SH}$  and  $\text{NH}_3$  cloud layer at  $\sim 2$ – $4$  bars and an  $\text{H}_2\text{O}$  cloud condenses somewhat deeper. Above the  $\text{NH}_3$  cloud deck, a stratospheric haze resides at pressures near  $\sim 0.1$  bar. It is worth mentioning that the Galileo probe results deviate from this standard model. One difference relevant to the albedo and reflection spectra is a tropospheric haze inferred from the probe data, likely composed primarily of  $\text{NH}_3$ , above a somewhat deeper  $\text{NH}_3$  cloud deck (Banfield et al. 1998), but it is not known whether the probe entry location is characteristic of the planet as a whole.

In addition to  $\text{H}_2$ , abundant gaseous species in the upper troposphere include He and  $\text{CH}_4$ , with mixing ratios relative to  $\text{H}_2$  of  $0.156$  and  $\sim 2.1 \times 10^{-3}$ , respectively (Niemann et al. 1996). Gaseous  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}$ , and  $\text{PH}_3$  are present in small mixing ratios.

It is suggested that the color differences of Jupiter’s belts and zones are largely due to the visibility of chromophores residing within the  $\text{NH}_3$  cloud deck (West et al. 1986). No appreciable altitude differences between the belts and zones are found, although the zones likely contain thicker upper cloud and/or haze layers than the belts (Chanover et al. 1997; Smith 1986). Jupiter’s UV/blue albedo is depressed substantially from what one would expect from the increase with frequency of the Rayleigh scattering cross sections, and Raman scattering cannot account for the albedo in this wavelength region. This depressed UV/blue albedo likely is produced by the large imaginary refractive indices of the tropospheric chromophores and, to a lesser degree, stratospheric aerosols (West et al. 1986).

Due to the large optical depth of Jupiter’s upper ammonia cloud deck at visible and near-infrared wavelengths, a two-cloud model of the atmosphere suffices (West 1979;

Kuehn & Beebe 1993). We model the top of the upper cloud deck ( $\sim 0.35$  bar) with a “cloud” distribution (see §??) peaked at  $0.5\mu\text{m}$ . Deeper in the cloud, from  $0.45$  to  $0.7$  bar, a particle distribution peaked at  $30\mu\text{m}$  is used. This size distribution is also utilized in the lower cloud, spanning  $2$  to  $4$  bars.

In addition to  $\text{NH}_3$  condensation, a small mixing ratio of a chromophore, either tholin ( $2 \times 10^{-8}$ ) or  $\text{P}_4$  ( $5 \times 10^{-9}$ ), is added to the upper cloud. As inferred from limb darkening observations, the condensed chromophore becomes well mixed in the upper ammonia cloud, and perhaps deeper as well (West et al. 1986; Pope et al. 1992). As per Noy et al. (1981), the peak of the chromophore particle size distribution is set to  $0.05\mu\text{m}$ . However, the nature of the size distribution and whether the chromophore adheres to the ammonia ice particles are as yet unclear.

Gaseous abundances are modeled using the Galileo Probe Mass Spectrometer values (Niemann et al. 1996) as a guide. The  $\text{H}_2$ , He, and  $\text{CH}_4$  abundances are taken directly from the Probe results. However, the tropospheric  $\text{NH}_3$  abundance varies considerably with depth. At  $\sim 0.4$  bar, its mixing ratio has been found to be  $\sim 5 \times 10^{-6}$  (Griffith et al. 1992; Kunde et al. 1982), while at  $\sim 0.7$  bar, its mixing ratio is  $\sim 5 \times 10^{-5}$  to  $10^{-4}$ . In an infrared study using Voyager IRIS data (Gierasch et al. 1986), it was found that only a small fraction ( $\sim 1\%$ ) of the ammonia is in condensed form. Based on our visible albedo modeling, where the smaller particle size distribution dominates, and using the gaseous  $\text{NH}_3$  mixing ratios above, we find that a condensation fraction of  $\sim 5\%$  in the upper cloud is required to provide the necessary reflectance.

We model Jupiter’s stratospheric haze using Deirmendjian’s “haze” particle size distribution (see §??) of polyacetylene peaked at  $0.1\mu\text{m}$ —a particle size justified by limb darkening studies (Rages et al. 1997; West 1988; Tomasko et al. 1986). The abundance of  $\text{C}_2\text{H}_2$  in Jupiter’s stratosphere is  $\sim 10^{-8}$  to  $10^{-7}$  (Edgington 1998; Noll et al. 1986), though the polymerized abundance is not known. In this study, the polyacetylene mixing ratio is set to  $5 \times 10^{-8}$ , in a haze layer from  $0.03$  to  $0.1$  bar.

Figure 5 shows two model geometric albedo spectra along with the observed full-disk albedo spectrum of Jupiter (Karkoschka 1994). We convert our model spherical albedo to a geometric albedo using an averaged phase integral of  $q = 1.25$  (Hanel et al. 1981). The upper model utilizes tholin as the chromophore throughout the upper ammonia cloud deck, while the lower model utilizes  $\text{P}_4$ .

Although the general character of Jupiter’s geometric albedo is reproduced fairly well, many of the methane absorption features are modeled too deeply. Furthermore, the gaseous ammonia features at  $\sim 0.65\mu\text{m}$  and  $0.79\mu\text{m}$  do not appear in the models because our database does not include ammonia absorption shortward of  $\sim 1.4\mu\text{m}$ . Karkoschka (1998) indicates that the absorption feature centered at  $\sim 0.93\mu\text{m}$  may be due to ammonia as well. Relying upon Mie scattering theory and our choices for chromophore particle size distributions, tholin appears to reproduce the UV/blue region of the albedo better than  $\text{P}_4$ . However, the actual chromophore(s) in Jupiter’s atmosphere remains a mystery.

The published Bond albedo of Jupiter is  $0.343$  (Hanel et al. 1981). Using our models and limited wavelength coverage ( $0.3\mu\text{m}$  to  $2.5\mu\text{m}$ ), we estimate a Bond albedo



(see §??) in the 0.42 to 0.44 range—a fair approximation—depending upon whether  $P_4$  or tholin is used as the chromophore.

Uncertainties in the vertical structure of Jupiter’s atmosphere, heterogeneities in Jupiter’s cloud layers, and our use of an averaged phase integral all likely play a role in explaining the differences between observational and modeled albedo spectra. These details aside, Jupiter’s atmosphere remains a useful benchmark for our models of EGP albedo and reflection spectra.

## 7. RESULTS FOR EGPS

We produce fiducial albedo models for each EGP class using both isolated and modified temperature-pressure profiles. We adopt Deirmendjian’s “cloud” particle size distribution with a peak at the moderate size of  $5\ \mu\text{m}$ . Our model EGP spherical albedos for the full range of effective temperatures are shown in Figures 6 through 8. For these fiducial models, “full condensation” is assumed (as described in §2.3).

The “Jovian” Class I albedo spectra are determined mainly by the reflectivity of condensed  $\text{NH}_3$  and the molecular absorption bands of gaseous  $\text{CH}_4$ . Stratospheric and tropospheric non-equilibrium species are not included in these fiducial models. Their effects are explored in §??. Because both isolated and nearly “isothermal” T-P profiles of EGPs with  $T_{\text{eff}} \lesssim 150\ \text{K}$  cross the  $\text{NH}_3$  condensation curve, the details of the T-P profiles do not have a large impact on the resulting albedos of Class I objects. As shown in Figure 6a, the reflective  $\text{NH}_3$  clouds keep the albedo fairly high throughout most of the visible spectral region. Toward the infrared, the gaseous absorption cross sections tend to become larger, so photons are more likely to be absorbed above the cloud deck. Hence, at most infrared wavelengths, the albedo is below that in the visible region.

The isolated and modified profile Class II albedos are shown in Figure 6b. Relative to a Class I EGP, a Class II albedo is even higher in the visible due to very strongly reflective  $\text{H}_2\text{O}$  clouds in the upper atmosphere. Gaseous absorption features tend to be shallower because these  $\text{H}_2\text{O}$  clouds form higher in the atmosphere than the  $\text{NH}_3$  clouds of most Class I objects. The intersection of the isolated profile and the  $\text{NH}_3$  condensation curve near 0.01 bars may result in a thin  $\text{NH}_3$  condensation layer high in the atmosphere, but  $\text{NH}_3$  condensation is assumed to be negligible for this model.

The “clear” Class III does not contain any principal condensates in the upper atmosphere (irrespective of the T-P profile), although a silicate cloud deck exists deeper, at  $\sim 50$  bars. The presence of alkali metals in the troposphere has a substantial lowering effect on the albedo. As per Figure 7a, sodium and potassium absorption lowers the albedo at short wavelengths, resulting in a spherical albedo below  $\sim 0.6$  throughout most of the UV/blue spectral region. Into the red region, lower Rayleigh scattering cross sections and strong alkali metal absorption result in spherical albedos which drop below 0.1. In contrast, in the absence of the alkali metals, the spherical albedo would remain high ( $\gtrsim 0.75$ ) throughout most of the visible. In both cases, the near-infrared albedo is essentially negligible, largely due to absorption by  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ , and  $\text{H}_2\text{-H}_2$  CIA. Our models show that, in Class III objects,

the details of the T-P profile will have only minor effects on the albedo. If low-abundance sulfide or chloride condensates were to exist in the troposphere, they could appear at pressures as low as a few bars. Based on theoretical abundances (Burrows & Sharp 1999), thick clouds are very unlikely, but it is worth mentioning that even cirrus-like condensation could raise the albedo in the visible and near-infrared.

In the higher-temperature ( $900\ \text{K} \lesssim T_{\text{eff}} \lesssim 1500\ \text{K}$ ) Class IV roasters, the effect of the alkali metals is most dramatic. Unlike the Class III EGPs, a silicate cloud deck exists at moderate pressures of  $\sim 5\text{--}10$  bars, depending on the details of the T-P profile. An iron or iron-rich condensate likely exists below the silicate deck, but it is sufficiently below the opaque silicate cloud that it does not have any effect on the visible and near-infrared albedos. Figure 7b shows the spherical albedo of a Class IV EGP. Assuming a fairly “isothermal” T-P profile (the modified profile) in the upper atmosphere, absorption by sodium and potassium atoms, coupled with ro-vibrational molecular absorption, results in a surprisingly low albedo throughout virtually the entire visible and near-infrared wavelength region explored in this study ( $\leq 2.5\ \mu\text{m}$ ). The silicate cloud is deep enough that its effects are rendered negligible by the absorptive gases above it.

Although a Class IV model with a modified T-P profile results in an albedo which is significantly lower than that of even a Class III model, the albedo of a Class IV model with an isolated T-P profile is a different story: Because the upper atmosphere in such a model is significantly cooler than in the modified T-P profile case, the equilibrium abundances of the alkali metals are lower. Furthermore, the silicate cloud deck is expected to be somewhat higher in the atmosphere (Figure 1) and to have a non-negligible effect on the albedo in both the visible and near-infrared regions (Figure 7b).

Due to the low ionization potentials of sodium (5.139 eV) and potassium (4.341 eV), it is likely that significant Na II and K II layers exist in the outer atmospheres of Class IV EGPs (and perhaps Class III EGPs). Nevertheless, assuming a silicate cloud layer at  $\sim 5\text{--}10$  bars, simple ionization equilibrium estimates indicate that these layers should not reach the depths of the silicate layer in Class IV EGPs, and so substantial column depths of Na I and K I should remain to absorb visible radiation. The full absorption and emission features of such ionization layers will be explored in future EGP studies.

The very hot ( $T_{\text{eff}} \gtrsim 1500\ \text{K}$ ) Class V roasters have a silicate cloud layer which is located much higher in the atmosphere relative to the Class IV roasters, so alkali metal and molecular absorption is reduced. Figure 7b illustrates the much higher albedo expected of the Class V objects, assuming the silicate layer is composed predominantly of enstatite grains. If the sodium and potassium ionization layers are substantial in these objects, then the absorption due to their neutral lines will be reduced even further. We also note that a roaster of particularly low mass (e.g. HD 209458b) is expected to exhibit a significantly larger radius than such an object in isolation (Burrows et al. 2000). For such a low surface gravity ( $\lesssim 10^3\ \text{cm s}^{-2}$ ) object, the silicate layer will form high in the atmosphere even for  $T_{\text{eff}} < 1500\ \text{K}$ . Hence, the lower limit to  $T_{\text{eff}}$  required to render a roaster a Class V EGP is reduced in the case of low

surface gravity.

Via spectral deconvolution, Charbonneau et al. (1999) have constrained the geometric albedo of the roaster,  $\tau$  Boo b, to be below 0.3 at  $0.48 \mu\text{m}$ . This limit, which was obtained with an assumed phase function and orbital inclination near 90 degrees, contrasts with the findings of Cameron et al. (1999), who infer that the albedo is high in this region. Using our Class IV T-P profile model ( $T_{\text{eff}} \lesssim 1500 \text{ K}$ ), we find that the geometric albedo at  $0.48 \mu\text{m}$  is only 0.03. However, if in fact  $\tau$  Boo b is a Class V EGP ( $T_{\text{eff}} \gtrsim 1500 \text{ K}$ ), we derive a geometric albedo of 0.39 at  $0.48 \mu\text{m}$ , still smaller than the assumed Cameron et al. value of 0.55, from which they derive a planetary radius as high as 1.8 Jupiter radii. The widely varying albedos of Classes IV and V coupled with the fact that  $\tau$  Boo b appears to have an effective temperature near the transition region between these classes indicates that the detailed modeling of this EGP will be necessary in order to ascertain its nature.

It is instructive to examine the temperatures and pressures to which incident radiation penetrates an EGP's atmosphere as a function of wavelength. For each class, Figures 9 and 10 show the pressures and temperatures, respectively, corresponding to one mean free path of an incident photon. In clear atmospheres, these temperatures and pressures are very strong functions of wavelength, largely mirroring molecular absorption bands and/or atomic absorption lines. Conversely, when thick cloud layers are present, the wavelength dependence is much weaker, due to the efficient extinction of radiation by a size distribution of condensed particles.

Due to the azimuthal symmetry of our Feautrier technique, we do not compute the phase integrals of EGPs. In their absence, the characteristics of the atmosphere at  $\tau_\lambda \sim 1$  are useful for the approximate conversion from spherical albedos to geometric albedos. Using the asymmetry factor and single scattering albedo values, the phase integral,  $q_\lambda$ , is estimated by interpolating within the tables of Dlugach & Yanovitskij (1974) (Marley et al. 1999). Geometric albedos are then obtained using the relation,  $A_{g,\lambda} = A_{s,\lambda}/q_\lambda$ . Estimated geometric albedo spectra are shown in Figure 11. Our Class II geometric albedo compares qualitatively with that of the “quiescent” water cloud model of Marley et al. (1999). Given the differences in particle size distributions, the Marley et al. albedo tends to fall off a bit more sharply with increasing wavelength, while having shallower gaseous absorption features in the visible. Our Class IV models may be compared with the Marley et al. “brown dwarf” model with silicate (enstatite) clouds, as well as with the 51-Peg b model of Goukenleuque et al. (1999). Our inclusion of the alkali metals results in a qualitatively very different, and much lower, albedo spectrum than in these previous studies. Our Class V model may be compared with the high-temperature model ( $T_{\text{eff}} = 1580 \text{ K}$ ) of Seager & Sasselov (1998). We find that, similar to Seager & Sasselov, the presence of silicate (enstatite) grains results in significant reflection, but our inclusion of the alkali metals results in prominent absorption lines as well.

We combine a geometric albedo spectrum from each EGP class with appropriately calibrated stellar spectra (Silva & Cornell 1992) to produce representative EGP re-

flection spectra. Figure 12a shows theoretical full-phase reflection spectra of EGPs from  $0.35 \mu\text{m}$  to  $1.0 \mu\text{m}$ , assuming a G2V central star, orbital distances of 0.05 AU (Class IV), 0.2 AU (Class III), 1.0 AU (Class II), and 5.0 AU (Class I), and a planetary radius of 1 Jupiter radius ( $R_J$ ). For a Class IV roaster, at  $0.45 \mu\text{m}$ , the ratio of reflected and stellar fluxes is  $\sim 5 \times 10^{-6}$ , while for Class I, II, and III EGPs, it is  $\sim 5 \times 10^{-9}$ ,  $10^{-7}$ , and  $10^{-6}$ , respectively. This ratio at  $0.65 \mu\text{m}$  drops to  $\sim 5 \times 10^{-7}$  for a Class IV object, and is  $\sim 5 \times 10^{-9}$ ,  $10^{-7}$ , and  $3 \times 10^{-7}$  for Class I, II, and III EGPs, respectively. Figure 12b shows theoretical full-phase reflection spectra of Class IV and V roasters, assuming an F7V central star, orbital distances of 0.1 AU (Class IV) and 0.04 AU (Class V), and 1  $R_J$ . At  $0.45 \mu\text{m}$ , the reflected to stellar flux ratios are  $\sim 10^{-6}$  (Class IV) and  $5 \times 10^{-5}$  (Class V). At  $0.65 \mu\text{m}$ , these ratios are  $\sim 10^{-7}$  (Class IV) and  $5 \times 10^{-5}$  (Class V). For larger planetary radii and different orbital distances, these ratios should be scaled accordingly.

In the reflection spectrum of a Class IV object (Figure 12), absorption by the resonance lines of sodium ( $5890\text{\AA}/5896\text{\AA}$ ) and potassium ( $7665\text{\AA}/7699\text{\AA}$ ) is extreme. These lines are also very significant, though substantially weaker, in Class III objects. Methane absorption bands shortward of  $1 \mu\text{m}$ , especially those at  $\sim 0.73 \mu\text{m}$ ,  $0.86 \mu\text{m}$ , and  $0.89 \mu\text{m}$ , are quite prominent in Class I and III objects. These bands are also clearly present in Class II objects, but with sufficient water condensation high in the troposphere, the bands are not as prominent as in Class I or Class III EGPs. Although present, methane absorption is even weaker in Class IV EGPs, where CO is the dominant carbon-bearing molecule. At the high effective temperature of a Class V object ( $T_{\text{eff}} \gtrsim 1500 \text{ K}$ ), the methane abundance is completely overwhelmed by that of CO, and we expect that no strong methane bands will be seen in reflection.

Bond albedos for EGPs are obtained using eq. (5). Our lower and upper wavelength limits of integration are  $0.3 \mu\text{m}$  and  $2.5 \mu\text{m}$ , respectively, rather than formally from 0 to infinity. Hence, our derivations are estimates of actual Bond albedos, accurate to  $\sim 10\text{-}15\%$ , depending on the central stellar spectral type and the uncertainties in the EGP spherical albedos shortward of  $0.3 \mu\text{m}$  and longward of  $2.5 \mu\text{m}$ . The Bond albedos for our fiducial modified T-P profile models and for isolated T-P profile models are shown in Tables 1a and 1b. Assuming full condensation of principal condensates and no non-equilibrium species, the Bond albedos of Class I and II objects are high. Over the spectral range, M4V to A8V, the peak of the stellar energy flux ranges from  $\sim 0.9 \mu\text{m}$  to  $0.4 \mu\text{m}$ . Class I EGP Bond albedos range from  $\sim 0.4$  to  $0.65$ , while those of Class II EGPs reach nearly 0.9. These albedos tend to be significantly lower when smaller condensation fractions and non-equilibrium condensates are considered. For example, the Bond albedo of our Jupiter model about a G2V central star is in the 0.42 to 0.44 range, depending upon whether  $P_4$  or tholin is used as the chromophore—somewhat higher than Jupiter's actual Bond albedo of 0.343 (Hanel et al. 1981).

In contrast, Bond albedos of Class III and IV EGPs are very low. Those of Class III objects vary from  $\sim 0.01$  to 0.2 over the spectral range, M4V to A8V. Class IV EGPs re-

flect the smallest fraction of incident radiation, with Bond albedos ranging from below 0.01 up to only 0.04, assuming our modified T-P profile model and no non-equilibrium condensates. These Bond albedos are significantly lower than those of Marley et al. (1999) because we include the effects of the alkali metals. For example, assuming a G2V central star, our fiducial Class III model yields a Bond albedo of 0.12, while those of Marley et al. are in the 0.31 to 0.33 range (cloud-free 500 K models), and our Bond albedo for a Class IV EGP is only 0.03, while those of Marley et al. are in the 0.30 to 0.44 range (cloud-free and cloudy 1000K models). The Bond albedos of the very hot Class V objects are much higher than those of Class III or IV, ranging from  $\sim 0.51$  to  $0.57$  over the spectral range, M4V to A8V.

Estimated Bond albedos and effective temperatures of known EGPs are shown in Tables 2 through 4. The equilibrium temperature of an irradiated object is

$$T_{\text{eq}} = \left[ \frac{(1 - A_B)L_*}{16\pi\sigma a^2} \right]^{1/4} \quad (33)$$

(Saumon et al. 1996), where  $L_*$  is the stellar luminosity,  $\sigma$  is the Stefan-Boltzmann constant, and  $a$  is the orbital distance of the planet. For massive and young EGPs with sufficiently large orbital distances,  $T_{\text{eff}} > T_{\text{eq}}$  due to their significant internal energies. We estimate the effective temperatures of such objects simply by adding the stellar-insolated and internal contributions to the luminosity, and noting that  $L = 4\pi R_p^2 \sigma T_{\text{eff}}^4$ . The internal contribution is defined to be the luminosity of an isolated object of the given mass and age, and it is found using the evolutionary models of Burrows et al. (1997).

Given the list of over two dozen known EGPs, it is possible that none is cold enough to be a Class I (“Jovian”) object (HR 5568b is an ambiguous case). Classes II, III, and IV are well-represented (Tables 2 through 4), while Class V likely includes HD 209458b, and perhaps  $\tau$  Boo b and/or HD 75289b.

## 8. PARAMETER STUDIES

In EGP atmospheres, variations in condensation fractions and particle size distributions, as well as the possible presence of stratospheric and tropospheric non-equilibrium species, can have large effects on the spherical and Bond albedos. First, we consider the effects of lowering the condensation fraction to 10% and 1%. Figures 13a and 13b show the substantial changes in Class I (“Jovian”) and Class II (“water cloud”) EGPs. The Class II case best illustrates the systematic effects, since only an  $\text{H}_2\text{O}$  cloud deck exists. (Recall that the Class I model contains an ammonia cloud deck above a water cloud deck.) The condensation fraction has a substantial effect on the spherical and geometric albedos. Less condensation clearly results in lower albedos, especially in the red/near-infrared, where gaseous opacities are strong (Marley et al. 1999). Note that the effects of the alkali metals, deep in the atmosphere, are apparent in the UV/blue albedo of the Class II, 1% condensation model. As shown in Tables 1a and 1b, the Bond albedos of these 1% condensation models are significantly lower than those of their “full condensation” counterparts, particularly for the Class II EGPs.

Cloud particle size distributions in EGPs are not known. As alluded to in §??, for a given condensate abundance, the net extinction by condensates (almost pure scattering for  $\text{H}_2\text{O}$  ice) is smaller when particle sizes are larger. This is shown explicitly in Figure 14a, comparing spherical albedos for Deirmendjian  $\text{H}_2\text{O}$  ice “cloud” distributions with size peaks of  $0.5 \mu\text{m}$ ,  $5 \mu\text{m}$  (fiducial), and  $50 \mu\text{m}$ . The qualitative effect of increasing the peak size is similar to the effect of reducing the condensation fraction. Widening the distribution has similar consequences because the largest particles squander the condensate, reducing the number density of smaller scattering particles.

Non-equilibrium species in the upper atmospheres of EGPs may be produced by UV-induced processes. While both gaseous and condensed species are likely to be produced, the condensates will generally have greater effects on the albedos and reflection spectra. As in the atmosphere of Jupiter, stratospheric hazes and tropospheric chromophores, or impurities within or above the principal cloud layers, can lower the albedo spectra in the UV/blue range and can also modify their character at other wavelengths. In addition to their compositions, the size distributions of these non-equilibrium species play a role. Figure 14b shows the effect of including a representative upper tropospheric “haze” of tholin (with mixing ratio of  $10^{-8}$ ) on the spherical albedo of a Class I EGP. In analogy with our Jupiter model, the size distribution is peaked at  $0.05 \mu\text{m}$ . Although the abundances and size distributions of such particles in EGPs are unknown, we present this model as an indication of the qualitative effect that this type of haze would have on the albedo. The associated Class I Bond albedo, assuming a G2V central star, decreases from 0.57 to 0.48.

We represent the optically dominant aerosol within stratospheric hazes by polyacetylene, although other possibilities certainly exist. Our models show that the effect of polyacetylene on the albedo is minor, lowering the UV/blue albedo no more than a few percent, assuming a mixing ratio as large as  $10^{-7}$ . We stress that the actual compositions, abundances, and the size distributions of non-equilibrium species in EGPs are unknown, and that the quantitative effects on EGP albedos may or may not be significant.

## 9. CONCLUSIONS

The classification of EGPs into five composition classes, related to  $T_{\text{eff}}$ , is instructive, since the albedos of objects within each of these classes exhibit similar features and values. The principal condensate in Class I “Jovian” EGPs ( $T_{\text{eff}} \lesssim 150 \text{ K}$ ) is  $\text{NH}_3$ , while in Class II “water cloud” EGPs it is  $\text{H}_2\text{O}$  ice. Gaseous molecular absorption features, especially those of methane, are exhibited throughout Class I and II albedo spectra. Assuming adequate levels of condensation, Class II EGPs are the most highly reflective of any class. For lower condensation fractions, the albedos of both classes fall off more quickly with increasing wavelength relative to “full condensation” models—especially the Class II objects. Even a small mixing ratio of a non-equilibrium tropospheric condensate within or above a cloud deck can depress the UV/blue albedo and reflection spectrum significantly.

In Class III “clear” EGPs ( $T_{\text{eff}} \gtrsim 350 \text{ K}$ ), little condensation is likely, and so albedos are determined al-

most entirely by atomic and molecular absorption and Rayleigh scattering. Radiation generally penetrates more deeply into these atmospheres, to pressures and temperatures where sodium and potassium absorption and H<sub>2</sub>-H<sub>2</sub> collision-induced absorption (CIA) become substantial. Throughout most of the visible spectral region, the albedo decreases with increasing wavelength. In the near-infrared, CIA, H<sub>2</sub>O, and CH<sub>4</sub> conspire to keep the albedo very low.

In the upper atmospheres of the high-temperature (900 K  $\lesssim$  T<sub>eff</sub>  $\lesssim$  1500 K) Class IV roasters, the equilibrium abundances of the alkali metals are higher than in the Class III EGPs, so the absorption lines of sodium and potassium are expected to lower the albedo more dramatically. A silicate cloud exists at moderate depths ( $\sim$  5–10 bars), but the large absorption cross sections of the sodium and potassium gases above it preclude the cloud from having a significant effect on the albedo. Like Class III EGPs, the near-infrared albedo is expected to remain close to zero in the absence of non-equilibrium condensates.

The hottest (T<sub>eff</sub>  $\gtrsim$  1500 K) and/or lowest gravity ( $g \lesssim 10^3$  cm s<sup>-2</sup>) roasters (Class V) have a silicate layer located much higher in the atmosphere relative to the Class IV roasters. This layer is expected to reflect much of the incident radiation before it is absorbed by neutral sodium and potassium and molecular species. Hence, Class V EGPs have much higher albedos than those of Class IV.

While stratospheres generally are not anticipated in high temperature EGPs (Seager & Sasselov 1998; Goukenleuque et al. 1999), it is possible that more detailed modeling will show that they do exist. The presence of a

stratosphere would give rise to visible and infrared emission features not otherwise seen. Furthermore, the presence of non-equilibrium solids due to photochemistry may decrease the albedo in the UV/blue, but increase it somewhat in the red/near-infrared because even largely absorbing condensates are more reflective than gaseous molecular species in this spectral region.

Differences in particle size distributions of the principal condensates can have large quantitative, or even qualitative effects on the resulting albedo spectra. In general, less condensation, larger particle sizes, and wider size distributions result in lower albedos.

Despite many uncertainties in the atmospheric details of EGPs, our set of model albedo spectra serves as a useful guide to the prominent features and systematics over a full range of EGP effective temperatures, from  $\sim$  100 K to 1700 K. Full radiative equilibrium modeling of a given EGP at a specific orbital distance from its central star (of given spectral type), and of specific mass, age, and composition is necessary for a detailed understanding of an object. However, as observational EGP spectra become available, our set of model albedo spectra offers a means by which a quick understanding of their general character is possible, and by which some major atmospheric constituents, both gaseous and condensed, may be inferred.

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FIG. 1.— Temperature-pressure profiles for each of the EGP classes of this study. Both isolated and modified (more isothermal) profiles are shown for Classes I through IV, as well as a modified profile for Class V. Also plotted are the condensation curves for some principal condensates, as well as the  $\text{NH}_3/\text{N}_2$  and  $\text{CH}_4/\text{CO}$  abundance equilibrium curves.

FIG. 2.— Comparison of our Asymmetric Feautrier code results to Monte Carlo and analytic solutions for deep, homogeneous atmospheres. The spherical albedo is plotted as a function of the single-scattering albedo ( $= \sigma_{\text{scat}}/\sigma_{\text{ext}}$ ) and the average value of the cosine of the scattering angle ( $g = \langle \cos \theta \rangle$ ).

FIG. 3.— Imaginary refractive indices of the principal condensates used in this study.

FIG. 4.— Imaginary refractive indices of stratospheric haze and tropospheric chromophore candidates. Tholin and  $\text{P}_4$  provide a great deal of absorption in the UV/blue.

FIG. 5.— The geometric albedo spectrum of Jupiter. Our model albedo spectra (thin curves) are compared with the observational full-disk albedo spectrum (thick curve, Karkoschka 1994). The top model utilizes tholin as a chromophore, while the bottom model uses  $\text{P}_4$ .

FIG. 6.— (a) The spherical albedo of a Class I “Jovian” EGP. Irrespective of the T-P profile, an  $\text{NH}_3$  cloud deck resides above an  $\text{H}_2\text{O}$  cloud deck. The thin curve corresponds to an isolated T-P profile model, while the thick curve signifies a modified, more isothermal profile model. (b) The spherical albedo of a Class II “water cloud” EGP. A thick  $\text{H}_2\text{O}$  cloud deck in the upper troposphere produces a high albedo. Isolated (thin curve) and modified (thick curve) T-P profile models are shown.

FIG. 7.— (a) The spherical albedo of a Class III “clear” EGP. In addition to the isolated (thin curve) and modified (thick curve) T-P profile models, the dashed curve depicts what the albedo would look like in the absence of the alkali metals. (b) The spherical albedo of a Class IV “roaster.” Theoretical albedo spectra of isolated (thin curve) and modified (thick curve) T-P profile Class IV models are depicted.

FIG. 8.— The spherical albedo of a Class V roaster. A silicate layer high in the atmosphere results in a much higher albedo than a Class IV roaster.

FIG. 9.— The log of the pressure (P) at a depth equal to the mean free path of incident radiation, as a function of wavelength ( $\lambda$ ) in microns, for each of the EGP classes. A size distribution of particles and the assumption of “full condensation” conspire to make the Class I and Class II curves only weak functions of wavelength.

FIG. 10.— The temperature (T) at a depth equal to the mean free path of incident radiation, as a function of wavelength ( $\lambda$ ) in microns, for each of the EGP classes.

FIG. 11.— (a) Estimated geometric albedos of Class I, II and III EGPs. A modified T-P profile model is used in each case. These conversions from spherical albedos are made by approximating the phase integral ( $q_\lambda$ ) based on the single scattering albedo and scattering asymmetry factor at an atmospheric depth equal to the mean free path of incident radiation. (b) Estimated geometric albedos of Class IV and V EGPs.

FIG. 12.— (a) Full-phase EGP reflection spectra, assuming a G2V central star, a planetary radius equal to that of Jupiter, and orbital distances of 0.05 AU (Class IV), 0.2 AU (Class III), 1.0 AU (Class II), and 5.0 AU (Class I). These reflection spectra are obtained by combining the geometric albedo of each EGP class with a G2V stellar spectrum (Silva & Cornell 1992) and a Kurucz (1979) theoretical spectrum longward of  $0.9 \mu\text{m}$ . (b) Full-phase EGP reflection spectra, assuming an F7V central star, a planetary radius equal to that of Jupiter, and orbital distances of 0.1 AU (Class IV) and 0.04 AU (Class V).

FIG. 13.— (a) The dependence of the spherical albedo of a Class I EGP on condensation fraction. “Full condensation” (thick curve), 10% condensation (thin curve), and 1% condensation (dashed curve) models are shown. (b) The dependence of the spherical albedo of a Class II EGP on condensation fraction. “Full condensation” (thick curve), 10% condensation (thin curve), and 1% condensation (dashed curve) models are shown.

FIG. 14.— (a) The dependence of the spherical albedo on the particle size distribution. Class II EGP models with Deirmendjian “cloud” distributions peaked at  $0.5 \mu\text{m}$  (thin curve),  $5 \mu\text{m}$  (fiducial; thick curve), and  $50 \mu\text{m}$  (dashed curve) are shown. Note that the alkali metals are not included in these model albedo spectra. (b) The effect of the presence of an upper tropospheric tholin haze (with mixing ratio of  $10^{-8}$ ) on a Class I EGP spherical albedo. The albedo-lowering effect is greatest in the UV/blue region of the spectrum.

TABLE 1A  
ESTIMATED BOND ALBEDOS OF EGPs

star	EGP class	fiducial	“isolated”	10% cond.	1% cond.
A8V	I	0.63	0.64	0.62	0.59
	II	0.88	0.88	0.79	0.47
	III	0.17	0.13		
	IV	0.04	0.21		
	V	0.57			
F7V	I	0.59	0.61	0.57	0.51
	II	0.84	0.83	0.74	0.40
	III	0.14	0.10		
	IV	0.03	0.18		
	V	0.56			
G2V	I	0.57	0.59	0.55	0.47
	II	0.81	0.81	0.71	0.37
	III	0.12	0.09		
	IV	0.03	0.16		
	V	0.55			

Bond albedos of EGPs, using modified T-P profile models (fiducial) with full condensation, isolated T-P profile models (“isolated”) with full condensation, modified T-P profile models with 10% condensation (10% cond.), and modified T-P profile models with 1% condensation (1% cond.). Because Class III and Class IV Bond albedos are not significantly affected by condensates, the columns referring to fractional condensation models are left blank. The existence of Class V is a result of very strong stellar insolation, so “isolated” T-P profile models are not calculated. In all cases, non-equilibrium condensates are ignored.

TABLE 1B  
ESTIMATED BOND ALBEDOS OF EGPs

star	EGP class	fiducial	“isolated”	10% cond.	1% cond.
G7V	I	0.55	0.58	0.52	0.44
	II	0.79	0.79	0.69	0.34
	III	0.10	0.07		
	IV	0.02	0.15		
	V	0.55			
K4V	I	0.48	0.52	0.44	0.33
	II	0.70	0.70	0.60	0.25
	III	0.05	0.04		
	IV	< 0.01	0.11		
	V	0.53			
M4V	I	0.38	0.43	0.33	0.16
	II	0.56	0.55	0.47	0.16
	III	0.01	< 0.01		
	IV	< 0.01	0.08		
	V	0.51			



TABLE 2A  
CLASS II EGPs (“WATER CLOUD”)

object	star	$M_{\text{psini}} (M_{\text{J}})$	$a$ (AU)	cond.	$A_B$	$T_{\text{eff}}$ (K)
Gl 876b	M4V	1.9	$\sim 0.2$	full	0.56	180
				10%	0.47	182
				1%	0.16	199
HR 5568b	K4V	0.75	$\sim 1.0$	full	-	-
				10%	-	-
				1%	0.25	160
HD 210277b	G7V	1.28	$\sim 1.15$	full	0.79	177
				10%	0.69	194
				1%	0.34	232
HR 810b	G0V	2.0	$\sim 1.2$	full	0.82	192
				10%	0.72	213
				1%	0.38	254

Class II EGPs and their central stars, masses, and orbital distances, along with estimated Bond albedos and effective temperatures, assuming various condensation fractions. Non-equilibrium condensates are ignored. Internal luminosities are estimated using the evolutionary models of Burrows et al. (1997) and assuming an age of 5 Gyr, except for HD 210277 b (8 Gyr), 47 UMa b (7 Gyr), and  $v$  And d (3 Gyr). An absence of albedo and  $T_{\text{eff}}$  entries indicates that for the expected EGP Bond albedo assuming the given condensation fraction,  $T_{\text{eff}}$  is low enough such that condensed ammonia, rather than water, should reside in the upper troposphere. Hence, this combination of parameters should not result in a Class II EGP.

TABLE 2B  
CLASS II EGPs (“WATER CLOUD”)

object	star	$M_{\text{psini}}$ ( $M_J$ )	$a$ (AU)	cond.	$A_B$	$T_{\text{eff}}$ (K)
16 Cyg Bb	G2.5V	1.66	1.7	full	0.81	158
				10%	0.71	170
				1%	0.37	198
47 UMa b	G0V	2.4	2.1	full	0.82	160
				10%	0.72	172
				1%	0.38	199
$\nu$ And d	F7V	4.61	2.50	full	0.84	228
				10%	0.74	233
				1%	0.40	247
Gl 614b	K0V	3.3	2.5	full	0.75	168
				10%	0.65	170
				1%	0.30	177
55 Cnc c	G8V	$\sim 5$	3.8	full	0.78	198
				10%	0.68	199
				1%	0.33	201

TABLE 3  
CLASS III EGPs (“CLEAR”)

object	star	$M_{\text{psini}}$ ( $M_J$ )	$a$ (AU)	$A_B$	$T_{\text{eff}}$ (K)
HD 130322b	K0V	1.08	0.08	0.07	810
55 Cnc b	G8V	0.84	0.11	0.10	690
Gl 86 Ab	K1V	4.9	0.11	0.07	660
HD 195019b	G3V	3.4	0.14	0.12	720
HD 199263b	K2V	0.76	0.15	0.07	540
$\rho$ Cr Bb	G0V	1.13	0.23	0.13	670
HR 7875b	F8V	0.69	$\sim 0.25$	0.14	650
HD 168443b	G8IV	5.04	0.277	0.10	620
HD 114762b	F9V	$\sim 10$	0.38	0.13	510
70 Vir b	G4V	6.9	0.45	0.11	380
$v$ And c	F7V	2.11	0.83	0.14	370

Class III EGPs and their central stars, masses, and orbital distances, along with estimated Bond albedos and effective temperatures. Non-equilibrium condensates are ignored.

TABLE 4  
CLASS IV EGPs (ROASTERS)

object	star	$M_{\text{psini}}$ ( $M_{\text{J}}$ )	$a$ (AU)	$A_B$	$T_{\text{eff}}$ (K)
HD 187123b	G3V	0.52	0.0415	0.03	1460
51 Peg b	G2.5V	0.45	0.05	0.03	1240
$\nu$ And b	F7V	0.71	0.059	0.03	1430
HD 217107b	G7V	1.28	0.07	0.02	1030

Class IV EGPs and their central stars, masses, and orbital distances, along with estimated Bond albedos and effective temperatures. Non-equilibrium condensates are ignored.































